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Original article

Coffee production in southern Saudi Arabian highlands: Current status and water conservation

Osama H. Sayed [a,*], Yahya S. Masrahi [a], M. Remesh [a], B.S. Al-Ammari [b]

[a] Biology Department, Faculty of Science, Jazan University, P.O. Box 2097 Jazan, Saudi Arabia
[b] Al-Imam Mohammad ibn Saud Islamic University, College of Science, Biology Department, Saudi Arabia

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ABSTRACT

Work aimed at assessing status and introducing water conservation regimes for coffee production in southern Saudi Arabian highlands. Data on farm locations, altitudes, areas, practices, irrigation, tree density, and annual coffee production were analyzed. Field experiment using chlorophyll fluorescence and different irrigation regimes was conducted to examine effects of reducing irrigation frequency on photosynthesis. Results indicated that *Coffea arabica* L. is commonly grown at altitudes of 1300–1400 m. Plants grown at 4–6 Trees m^{-2} using 100 kg ha^{-1} mineral fertilizer produce an average of 3 t ha^{-1}. High frequency 2-day-intervals irrigation regime practiced by farmers during the dry season presents ecological challenge to limited local artesian water resources. Changes in chlorophyll fluorescence under 14-day-intervals irrigation regime initiated water stress that markedly inhibited Photosystem II efficiency and quantum yield and increased non-photochemical energy dissipation. Applying a 7-day-intervals irrigation regime induced less inhibitory effects on Photosystem II. Results also indicated that shifting from 2-day-intervals irrigation regime to 7-day-intervals regime improves coffee agroecology and directs coffee production towards sustainability.

1. Introduction

Coffee is an important commodity and major crop in highlands of many countries (Gichimu et al., 2013; FAO, 2015). However, recent studies indicated that wild coffee is at extinction risk and deserves improved conservation programs (Davis et al., 2019). Coffee is thought to have originated in mountain forests of East Africa and was introduced to southern highlands of Arabian Peninsula (Pochet and Flémal, 2001; Anthony et al., 2002; Pohlan and Janssens, 2010; Davis et al., 2012; Al-Abdulkader et al., 2017). The genus *Coffea* (Rubiaceae) includes many species of which *C. arabica* L. accounts for most world coffee production (Anthony et al., 2010; Davis et al., 2006). This species is socioeconomically important and source of income for mountain farmers in south-western Saudi Arabia. Increased interest in coffee production led to accelerated research into coffee agriculture in the region (Al-Abdulkader et al., 2017; Mahdhi et al., 2017; Tounekti et al., 2017; Tounekti et al., 2018). In this region Fifa Mountain reaches altitude of 1800 m and coffee plantations rely on moderate temperature, high humidity, and rainfall. However, coffee has high water demand and drought spells affect quality and reduce yield (DaMatta and Ramalho, 2006; Cheserek and Gichimu, 2012). Coffee plants at Fifa Mountain experience water stress at midday during the dry season and irrigation using artesian water is common among farmers. This practice is serious threat to local artesian water reserves since farmers apply high frequency irrigation. However, sound coffee production pertains to sustainability that emanates in family farms with emphasis on linking production to conservation (Hanspal, 2010; Mithöfer et al., 2017; Samper and Quiñones-Ruiz, 2017). Coffee plantations at Fifa Mountain are family owned suitable for sustainable coffee production. Work in this paper aimed at assessing current status and yield of *C. arabica* L. crop at Fifa Mountain southwest of Saudi Arabia. Work also included field experiment with different irrigation regimes aimed at water conservation. Chlorophyll fluorescence technique was used to investigate effects of reduced irrigation frequency on coffee photosynthetic performance to optimize irrigation, enhance water conservation, and increase sustainability.

* Corresponding author.
E-mail address: oshsayed@gmail.com (O.H. Sayed).

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2. Materials and methods

The study was conducted in coffee farms at Fifa Mountain southwest of Saudi Arabia (17°15′N 43°06′E) at altitudes 1300–1400 m. Mean monthly air temperature and precipitation were obtained from Ministry of Environment, Water and Agriculture (Riyadh, Saudi Arabia). Data on farm locations, altitudes, areas, and agricultural practices including land preparation, seedling transplant, fertilizer application, and irrigation were obtained by interviews of 10 local coffee farm owners. Quantitative data on number of trees per unit area and annual coffee production were collected, analyzed, and presented as means and standard error was calculated. The five-year-old *C. arabica* L. trees grown in one of the farms were used as test material. The 8-weeks experiment carried out during growing season involved irrigation with local artesian water at 5 L Tree^{-1} in three irrigation regimes, namely; Regime 1 (2-day-intervals), Regime 2 (7-day-intervals), and Regime 3 (14-day-intervals). The 2-day-intervals Regime 1 is the high frequency irrigation regime applied by farmers. Chlorophyll fluorescence was measured every week at midday in intact 15-min dark-adapted *C. arabica* leaves (FMS2, Hansatech, Norfolk, England). Measured fluorescence parameters were the photochemical efficiency of open Photosystem II (PSII) reaction centers (Fv/Fm), quantum efficiency of PSII (ΦPSII), and non-photochemical quenching (NPQ) (Maxwell and Johnson, 2000; Sayed, 2003; Baker, 2008; Kalaji et al., 2016). All measurements were repeated ten times and standard error was calculated.

3. Results

Climatic records indicated mean monthly minimum air temperature of about 12.2 °C, maximum air temperature of about 25.6 °C, total annual precipitation of about 300 mm falling during the period June-October, and a 7-months-long dry season (Table 1).

Agricultural practices involve transplanting 90-days-old seedlings in lines 2.5 m apart and NPK fertilizer (25% N, 4% P, and 2% K) application at 100 kg ha^{-1}. Irrigation with artesian water at 2-day-intervals during dry season is common among farmers. Coffee plantations of 300–1500 m^2 were located at altitudes of 1300–1400 m with coffee trees planted at 4–6 Trees m^{-2} and coffee production in the range of 2.0–5.0 t h^{-1} with an average of about 3 t h^{-1} (Table 2).

Table 3
Chlorophyll fluorescence parameters in *C. arabica* under irrigation Regime 1 at 2-day-intervals, Regime 2 at 7-day-intervals, and Regime 3 at 14-day-intervals (mean ± se, n = 10).

Parameters	Irrigation Regime		
	Regime 1	Regime 2	Regime 3
Fv/Fm	0.84 ± 0.1	0.80 ± 0.2	0.63 ± 0.2
ΦPSII	0.83 ± 0.1	0.79 ± 0.3	0.60 ± 0.3
NPQ	0.01 ± 0.005	0.02 ± 0.008	0.05 ± 0.008

Chlorophyll fluorescence measurements under different irrigation regimes indicated that compared to Regime 1 practiced by farmers, Regimes 2 and 3 resulted in reduction of Fv/Fm of about 5% and 25%, respectively (Table 3). This reduction occurred with reduced ΦPSII of about 5% and 28% under Regimes 2 and 3, respectively (Table 3). Irrigation Regimes 2 and 3 also resulted in one-fold and five-fold increase in NPQ, respectively (Table 3).

4. Discussion

Coffee plantations are located at altitudes of 1300–1400 m at Fifa Mountain with mean monthly air temperature 12.2 °C and 25.6 °C for winter and summer, respectively (Table 1). Low temperature is due to high altitude and polar continental air influencing climate during winter (Fisher and Membery, 1998). Total annual precipitation of about 300 mm occurs during summer as tropical maritime air prevails in the region (Fisher and Membery, 1998). The species *C. arabica* L. grown at tropical altitudes higher than 1000 m requires cool temperatures for growth and warm temperatures for flowering (Pohlan and Janssens, 2010). Mean annual temperatures of 18–22 °C is optimal for growth higher than 25 °C accelerate fruit development (Cheserek and Gichimu, 2012; Tolessa et al., 2016). Hence, climatic norms at Fifa Mountain favour *C. arabica* L. agriculture.

Agricultural practices at Fifa Mountain include transplanting 90-days-old seedlings in lines 2.5 m apart. Fertilizer application (NPK) at 100 kg ha^{-1} during growing season appears to be important at these slopes with shallow clay-loam soil prone to nutrient depletion by torrents during rainy season (Masrahi, 2012). Fertilizer application was recommended for coffee production (Jaramillo-Botero et al., 2010; Chemora, 2014; Maro et al., 2014;

Table 1
Records of mean monthly climatic norms at the study site.

Parameter	Months											
	J	F	M	A	M	J	J	A	S	O	N	D
Min. Air Temp. (°C)	6	9	11	12	14	16	18	17	15	11	9	7
Max. Air Temp. (°C)	20	22	24	25	28	30	35	30	28	26	22	21
Precipitation (mm)	5.0	5.5	6.0	5.5	10.4	19.2	61.0	52.0	45.2	27.0	10.5	7.5

Table 2
Coffee production at Fifa Mountain southwest of Saudi Arabia (±se, n = 10).

Plantations	Altitude (m)	Area (m^2)	Number of Trees (Trees m^{-2})	Annual Production (t ha^{-1})
1	1300	300	4.0 ± 1.0	4.0 ± 0.1
2	1360	1500	4.6 ± 1.4	5.1 ± 0.4
3	1365	750	4.4 ± 1.1	3.0 ± 0.3
4	1365	750	5.4 ± 2.5	3.4 ± 0.2
5	1375	300	6.0 ± 2.6	2.5 ± 0.1
6	1380	800	6.5 ± 3.1	2.0 ± 0.1
7	1390	400	5.3 ± 2.3	2.0 ± 0.8
8	1390	600	6.1 ± 1.1	3.3 ± 0.2
9	1400	600	6.7 ± 3.4	3.0 ± 0.4
10	1400	300	4.6 ± 1.2	3.5 ± 0.3

Melke and Ittana, 2015; Temesgen and Tufa, 2017). Reported variable farm area of 300–1500 m^2 is due to rugged terrain of narrow terraced slopes at this mountainous region. In these farms coffee trees are grown at density of 4–6 Trees m^{-2} and produce an average of 3 t h^{-1} (Table 2).

Originating in African tropical high altitudes with abundant rainfall coffee has evolved a high water demand (Pochet and Flémal, 2001; Anthony et al., 2002; DaMatta and Ramalho, 2006; Davis et al., 2012). Reports indicated that *C. arabica* requires total annual rainfall of 300–2000 mm within 8-months-long rainy (DaMatta et al., 2007; DaMatta et al., 2008; Cheserek and Gichimu, 2012). Periods of drought during growing season initiate water stress and adversely affects quality and yield (Damatta, 2004; DaMatta and Ramalho, 2006; DaMatta et al., 2007; Cheserek and Gichimu, 2012; Mariga et al., 2016). Water stress in *C. arabica* induces changes in resources allocation favouring root development and increased root:shoot ratio (Silva et al., 2004; Dias et al., 2007; D'Souza et al., 2009; Worku and Astatkie, 2010; Kufa, 2012). Total annual rainfall of about 300 mm at Fifa Mountain falls short of *C. arabica* water requirements and plants experience water stress at midday during the long dry season. Therefore, irrigation using local artesian water in 2-day-intervals regime during the dry season is common among farmers. Furthermore, much of the data on effects of drought on coffee comes from experiments under controlled conditions (Tesfaye et al., 2008; Worku and Astatkie, 2010; King'oro et al., 2014; Tounekti et al., 2018). However, our 8-weeks irrigation regimes experiment was conducted in the field to gain information of high agronomic relevance on effects of irrigation frequency on photosynthesis in coffee plants. Results indicated that reducing irrigation frequency under irrigation Regimes 2 and 3 resulted in reduced Fv/Fm and ΦPSII (Table 3) reflecting reduced photochemical efficiency of open PSII reaction centers and reduced PSII quantum yield, respectively (Adams and Demmig-Adams, 2004; Baker, 2008; Kalaji et al., 2016). Observed increased NPQ with reduced PSII activity (Table 3) is indicative of increased fluorescence quenching and operation of photoprotective mechanism within photosynthetic apparatus (Adams and Demmig-Adams, 2004; Jahns and Holzwarth, 2012; Ruban and Belgio, 2014; Ruban, 2016). This photoprotective mechanism involves non-radiative excess energy dissipation. (Adams et al., 2006; Jahns and Holzwarth, 2012; Papageorgiou and Govindjee, 2014; Ruban and Mullineaux, 2014). Reports in the literature point to epoxidation-deepoxidation of xanthophyll cycle carotenoids as major mediator of photoprotection under stress conditions (Horton and Ruban, 2006; Murchei and Niyogi, 2011; Jahns and Holzwarth, 2012; Demmig-Adams et al., 2014; Ruban, 2016; Malnoë, 2018). Moreover, compared to farmers high frequency 2-day-intervals irrigation Regime 1, the 14-day-intervals Regime 3 initiated water stress that markedly inhibited PSII activity (Table 3). On the other hand, 7-day-intervals Regime 2 induced far less reduction of PSII activity (Table 3). Hence, shifting from high frequency 2-day-intervals to 7-day-intervals irrigation regime decreases irrigation frequency without marked effects on PSII activity. However, although measured fluorescence parameters clearly reflected short-term limitations of water shortage on coffee photosynthesis they might not directly be indicators of effects on coffee yield later in the season. Therefore, further long-term experiments using chlorophyll fluorescence are perhaps required to clarify effects of the proposed 7-day-intervals irrigation regime on coffee yield.

It can, therefore, be concluded that *C. arabica* L. is grown in farms of limited areas on high altitude terraces at Fifa Mountain with high frequency irrigation during dry season. Trees planted at 4–6 Trees m^{-2} with 100 kg ha^{-1} NPK fertilizer produce 3–5.5 t ha^{-1}. Chlorophyll fluorescence measurement under different irrigation regimes indicated applying 7-day-intervals irrigation regime induced tolerable reduction of PSII activity. Applying this 7-day-intervals irrigation regime improves coffee agroecology and directs coffee production towards sustainability.

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Conflict of interest

Authors declare that there are no conflicts of interest.

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